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Investigating the Challenges of Measuring Combination Mechanics in Textile Fabrics

M. Issam Yousef [1] (miy30@hw.ac.uk) and George K. Stylios (g.stylios@hw.ac.uk)

Research Institute for Flexible Materials RiFlEX, Heriot Watt University, UK

Abstract

Measurements of the mechanical behaviour of fabrics started during the Zeppelin ear in the 1900s, where tensile, shear and biaxial behaviour of the airship's envelope fabric were measured. More measurement methods were developed later when there was a need to measure fabric handle and behaviour. Although measurements of tensile, shear, buckling and bending have been established and being used; their combinations, which represents a more realistic approach, are still being developed. But these multi-axial measurements pose challenges not only in apparatus design but in determining the measurement parameters also. Here these challenges are being put forward and further research requirements are identified and discussed.

Keywords: Fabric measurements, fabric mechanics, biaxial testing, tensile, shear, and buckling.

1 - Introduction

Many ancient Greek and Roman sculptors displayed fabric behaviour manifested in the drape of their artifacts in a very realistic way, this topic is still in research until the present day (1). Engineering fabric properties has always been a vital need for the industry and it was boosted during the Zeppelin era in the 1900s (2), where the work of Haas in 1912 established fabric as engineering material by pioneering the study of fabric measurements and their mechanical properties (3). However, Pierce in 1930s

[1] Correspondence Author. Email: miy30@hw.ac.uk

followed with the measurement of fabric properties such as bending to determine fabric handle (1).

Fabrics are defined in many ways and their specification takes several forms. At the very basic level, which is regarded as basic but necessary for manufacturing, buying and selling, there is fabric weight, yarn type and count and weave or knit type. And then, depending on the fabric's end use, performance data will follow. Garment fabrics will have different data than upholstery, which will have different data from geotextiles. This enables fabric specification to determine its end application, but at the same time, it also creates difficulties determining what these requirements may be.

But all these specifications are based on properties measured in a single axis and at different loads depending on where the fabric will be used. This is generally acceptable and there is little argument that can be made. However fabrics as flexible materials, whether they are used for garments or for high performance, and they do not behave under one mode of deformation i.e. not in one axis but in combinations (4). This is irrespective to the load applied, which is low in garments and high in composites.

This area, although recognized, is still at its infancy. Attempts have been made to provide methods of measurement, of combined properties, but these have not enabled their further development and ultimate use. This is an attempt to critically investigate that research to establish its challenges and to provide suggestions for future measurement and instrumentations.

2 - Literature Review

Stylios (1) concluded that despite all the advances in nanotechnology and smart textile research fields, fabric measurement technologies are still very important and vital for the textile industry. He broadly outlined the developments of fabric measurements from the research of TEFO in Sweden in the 60's where the measurement fundamentals where established and reported, to the early 70's where the Kawabata Evaluation System (KES) was developed for accurate prediction of fabric handle and then to the creation of Fabric Assurance by Simple Testing (FAST) by CSIRO to predict the tailorability of fabrics.

In the early 70s, Kawabata studied fabric mechanics elaborately and produced detailed models, not only for the biaxial behaviour of woven fabric but also for bending, tensile and shear. With relating the system developed in these research to the handling properties of fabrics, the Kawabata Evaluation System (KES) was created and used as an approach to measure fabric mechanics in relation to apparel handling.

The KES measures the mechanical properties of textile fabrics at small deformation and low stress level, and it has been significantly studied in many publications (5-8). The system consists of four machine blocks, the tensile and shear tester that measures linearity of the curve, tensile energy, resilience, shear stiffness, hysteresis at 0.5°and hysteresis at 5°. The pure bending tester measures bending rigidity and the hysteresis of the moment. The compressibility tester also measures linearity of curve, compression energy and resilience. The KES surface tester measures the coefficient of friction and geometrical roughness.

Pan et al (9) concluded that the high inter-correlation between the measured parameters may duplicate the information and make it hard to interpret. On the other hand, Hu el al (10) referred to the shear property measured on the KES as not a pure shear thus can not be used to calculate the shear modulus and developed a calculation on their own to get the modulus from the shear rigidity calculated from KES.

The KES is a complex system, difficult to use and considered to be a scientific device for research (11-13). It is also very expensive equipment due to the sophisticated structure (1, 9) and the need of an experienced operator in order to run the tests and give effective implementation of the readings (14) That is why it has not been adopted by the industry (13).

In the 80s the Fabric Assurance System by Simple Testing system (FAST) was designed to measure the mechanical properties of fabric at low stress and the dimensional stability of fabrics (15), the system is used to predict performance and appearance in wear (11, 16, 17). The system has three testers; FAST1 is the compression meter, where the thickness at 2 g/cm^2 and 100 g/cm^2 are measured. FAST2, the bending meter, measures the bending rigidity using the cantilever concept, where a light cell measures the bending length. The extension meter, FAST3, measures the extension of fabric stripe in warp and weft direction and in biased under

5, 20 and 100 g/cm^2. From these values the Shear rigidity G and Formability can be calculated (11, 14, 16). The system doesn't provide enough data for complete stress-strain profile because it is limited to the given goods and it is considered to be more suitable for industry (1).

The shear in the FAST system uses a different shear concept from the KES system, the two concepts are illustrated in Figure 1. The KES shear is a simple shear in principle, where shearing force F is applied in the direction of one of the yarns set, W is the tensile force applied during the test and θ is the shearing angle making the shear resistance R (18)

$$R = \frac{F - W \tan\theta}{d} \; gf/cm \qquad (1)$$

In the bias extension test applied in the FAST shear equipment, the sample is cut at 45° bisecting the right angle between warp and weft in the fabric and F, the tensile force is applied to one side. The resistance in this case is calculated (18)

$$R = \frac{F}{2d} \; gf/cm \qquad (2)$$

The bias extension test is simple, easy and can be carried out on any extensometer and thus considered to be more suitable for industrial use (19, 20).

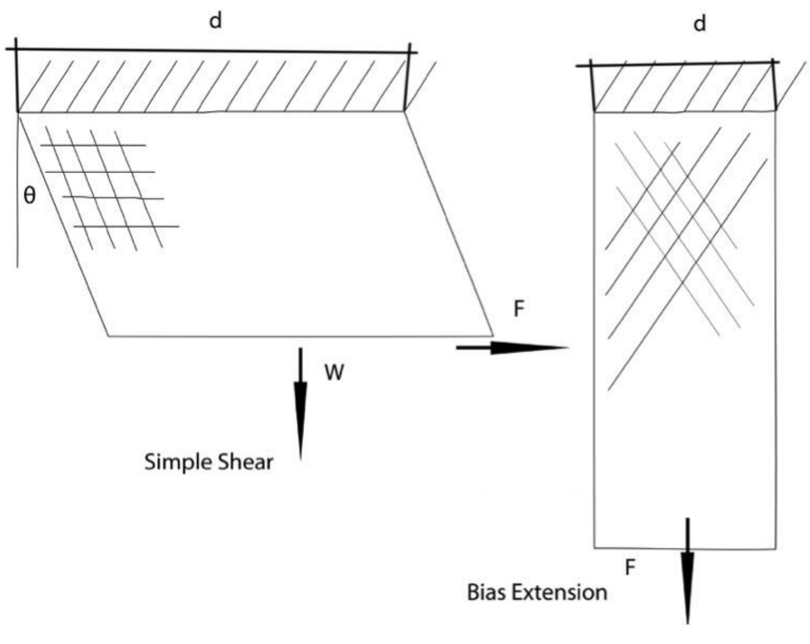

Figure 1: Concept of simple shear in (KES) (a), and bias extension (FAST) (b), image adapted from (19)

It is worth mentioning that a high correlation was found between the measurement of the extension and shear rigidity of the FAST 3 and the Kawabata tensile and shear meter KES 1 (21, 22). Moreover, a high correlation was reported in bending rigidity between FAST2 and KES-FB2 (12).

Pan et al (9) also used the bias cut sample to measure the shear properties on an extensometer, in an attempt to produce similar mechanical properties as the KES system. The tensile test was carried out normally by choosing a proper load or extension; the stress was kept lower than the breaking stress where the non-linear behaviour of the fabric is detected. For pure bending, a compression cell on a tubular sewn sample was used, to apply compression force to a given displacement. Compression and friction properties were measured by means of compression cell and a set of, pulley and sliding surface for the friction test. He concluded that the shear and bending curves he generated, were not similar to the Kawabata curves, as they were plotting different values, even though they reveal the same physical information. Leung et al (23) considered 7.5% extension as representative for a shear angle of 8°. The shear rigidity G is calculated from the slop of the linear regions of the curve, Figure 2. Despite the fact that they concluded high correlation between shear rigidity from the KES system and shear rigidity from the bias extension, they also highlighted that there is a difference between the Kawabata and the bias test, not due to the structure but due to the difference in method referring to Buckenham trellis deformation during shear (19, 23).

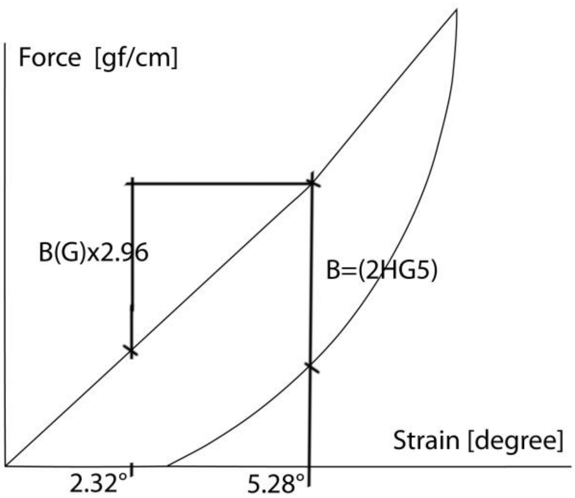

Figure 2: Shear graph produced by a bias sample on an extensometer, image adapted from (19)

However, there is a drawback in using bias samples to measure shear. The stress distribution is not homogeneous since the clamps do not allow any constrain near the end of the sample (24). The sample during the bias extension will have three major zones of deformation (20). On the other hand, Spivak (18) concluded that there is no relation between bias extension and shear, since shear is parallel to the warp and weft direction. Similarly, Pan et al (9) concluded that they are not similar to the Kawabata curves as they plot different values, however; they reveal the same physical information that shear curves do in the KES system. Hearle (25) studied different shear values and properties from different methods and he concluded that it is not worth describing all shear instruments as they share the same principle, this however, does not mean that there are no differences, but that they all can be reasonably ignored.

The bias extension concept is also used in the CHES-FY system developed by Zhaoqun (26-29), where the fabric is fixed by a pair of jaws and hung between a fixed pin connected to a sensor and U-shaped pins that lift the sample to stretch it between the U pins and the pin sensor. The tensile applied in this combination can be used to measure tensile with a normal sample and shear with a bias cut sample. Although Zhaoqun (29) concluded that the CHES-FY results were in correlation with the KES and FAST results, only bending was discussed in details while data for shear rigidity measurements were not reported.

Measuring shear properties did not start with the KES system, although it is currently the most common testing method. During the Zeppelin era in the early 1900s, Haas (3) used a novel method to measure the fabric shear properties by means of cylindrical fabric test. Later, Ckhadwic in 1949 used this method to calculate shear modulus by applying uniaxial tensile on a cylinder mountained at a bias angle (30), which according to Zheng et al (31) they could not present any results, Figure 3. In this test, a 24 cm length sample is being formed into a 4 cm diameter cylinder and clamped between two jaws, where one of them is attached to a balance arm with a protractor to indicate the twist angle of the fabric. Weights are added to a pan to twist the fabric to 30 - 35 degree in both directions, and the shear stress and shear strain are calculated according to Subramaniam and Sivakumar (30) as in Equation 1 and Equation 2 respectively.

$$Shear\ Stress = \frac{Fdcos\alpha}{2\pi rT} \qquad (3)$$

Where, F is the weight, d is the arm length between the weight F and the center, T is the specimen thickness and α is twist angle read by the protractor.

$$Shear\ Angle\ \phi = tan^{-1}\left(\frac{r\pi d}{180L}\right) \qquad (4)$$

Where, L is the distance between the clamps and r is the clamps radius.

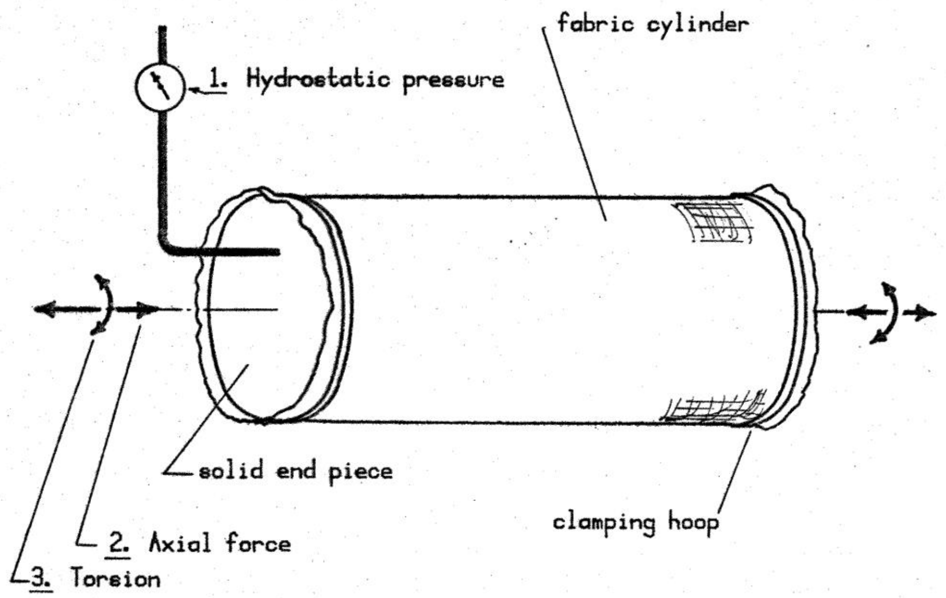

Figure 3: Cylindrical shear test, image adapted from (30)

Subramaniam and Sivakumar (30) concluded that this method gives realistic shear behaviour since it is being measured as its actual use in a cylinder form not as a flat specimen. In a later research, Subramaniam et al (32) concluded that applied torsion, specimen size, fabric sett and shear strain are the main factors that affect shear property. This method also considered as a method to measure the biaxial tensile when the cylindrically shaped fabric undergoes a compressive stress and internal surface pressure (33), but this measurement is not satisfactory because it doesn't cover all biaxial tensile aspects (34).

Many other methods to measure shear properties were also developed, according to Behre (35), Derby then Morner and Eeg-Olofsson were the first to use the disk attachment on Instron named as Planoflex. The measurement was made by means of an attachment to measure the angle between two shear limits when the fabric wrinkle,

Figure 4. The shear deformation is achieved by a wheel to transform the movement of the cross head of the Instron into circular movement for the wheel, which by mean of bars, bearing and weights will apply shearing force on a sample that is clamped to these mechanisms (35, 36).

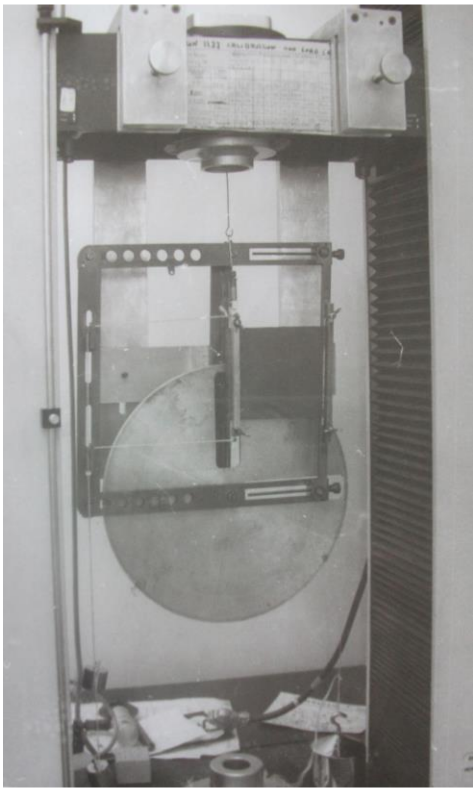

Figure 4: Shear using a disk on extensometer, image adapted from (36)

Other attachment on extensometers was also created by Culpin (37), where a square clamping frame is installed diagonally on tensile testing machine, Figure 5. However, Bassett et al (24, 38) considered that this method fail to achieve a homogeneous strain due to the wrong positioning of the pivots of the clamps, which cause buckling and slippage of the fabric edges near the clamped region.

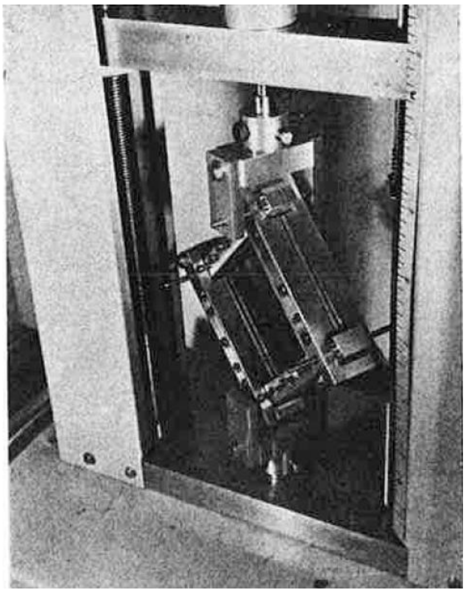

Figure 5: Culpin frame, image adapted from (37)

Bassett (24) also concluded that in the conventional two clamped sides shear tester, it is very difficult to apply homogeneous stress on the specimen, thus suggesting the need for more accurate measurement with four sides clamping to impose a uniform distribution.

Others worked to increase the complexity of the standard shear test by studying biaxial behaviour. Chang et al (39) measured the biaxial shear of fabrics by testing a bias cut cruciform sample on a biaxial tester, a microscope was used to highlight the microscopic changes of the geometry. Later, Harrison and Potluri (40) and Abdiwi et al (41) used the same method to investigate the effect of tension on the shear behaviour. Similarly, Prasad et al (42) applied biaxial tensile on a bias sample but in a rectangular shape, Figure 6, and claimed that this method eliminated the disadvantages of having a non-uniform shear distribution that comes form the other methods that uses cruciform.

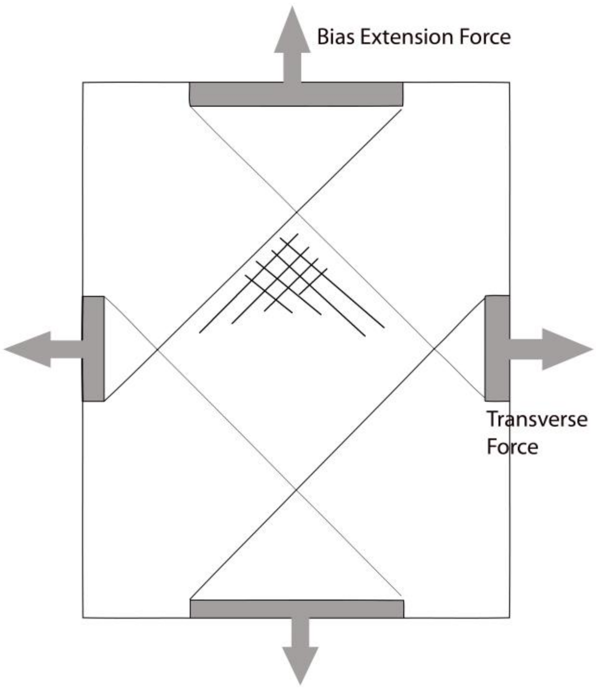

Figure 6: Bi-shear test scheme

This method can't compute the shear angle from the cross head movement as in the bias extension test but it can be calculated from the center square by drawing a cross on the sample prior the test as the center square is the one which indicates a full shear angle, while other areas can have half the shear angle and others no shear at all (43). Harrison et al (40, 43) used this method to measure the shear-tension coupling in a fabric and the onset of wrinkling as the shear angle of the fabric used can be up to 60° (42).

Early in the 19th century and specifically during the Zeppelin era, Haas (3) had to measure fabric strength, creep and biaxial stress/strain of rubber-coated linen fabrics (2, 44). Amongst these measurments, he was the first to develop and use a biaxial tester in 1912 for Siemens-Schukert (3, 24, 45). This device used a metal frame where two tensions can be applied on the cruciform fabric sample by means of two weights of sandbags, Figure 7. Haas was able to produce different results and was also able to calculate the distribution of the tension in the sample, as illustrated in Figure 8.

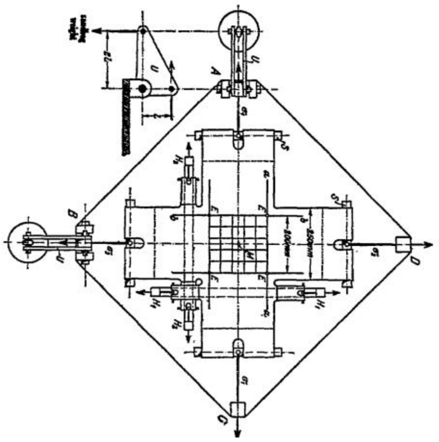

Figure 7: Haas biaxial tester schematic drawing. image adapted from (2)

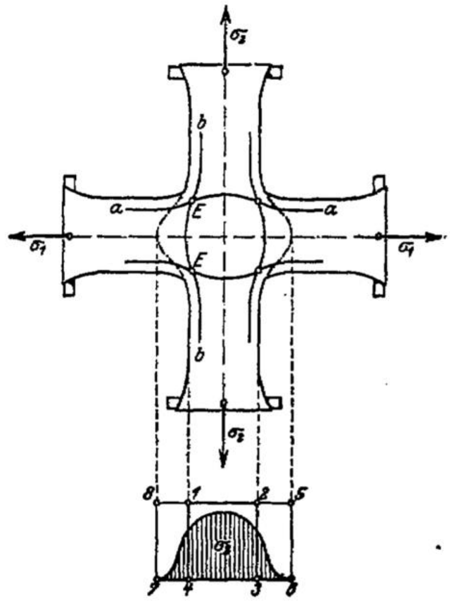

Figure 8: Stress distribution in the sample, image adapted from (2)

The development of biaxial testers continued with the measurement of rubber films, they were based on two perpendicular directions according to (46), but rubber being isometric provided little challenges in providing data results. Later, Checkland et al (47) developed a two direction tester based on a lathe chuck to strain the sample, Figure 9. Klein (48) created a biaxial tester that used a cruciform sample with flat clamps to hold the sample and were able to measure the stress and strain in both warp and weft directions, Figure 10. Clulow and Taylor (49) also developed a biaxial tester that used a cruciform sample, able to measure stress/strain of plain woven fabric, Figure 11.

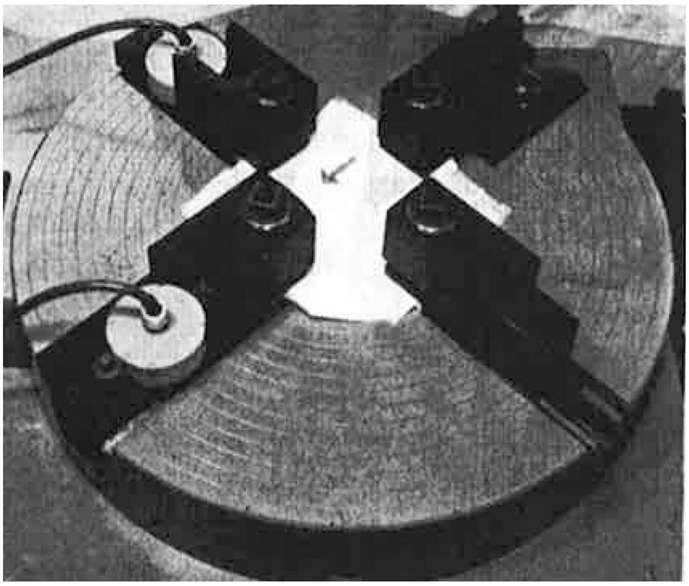

Figure 9: Checkland biaxial straining device, image adapted from (47)

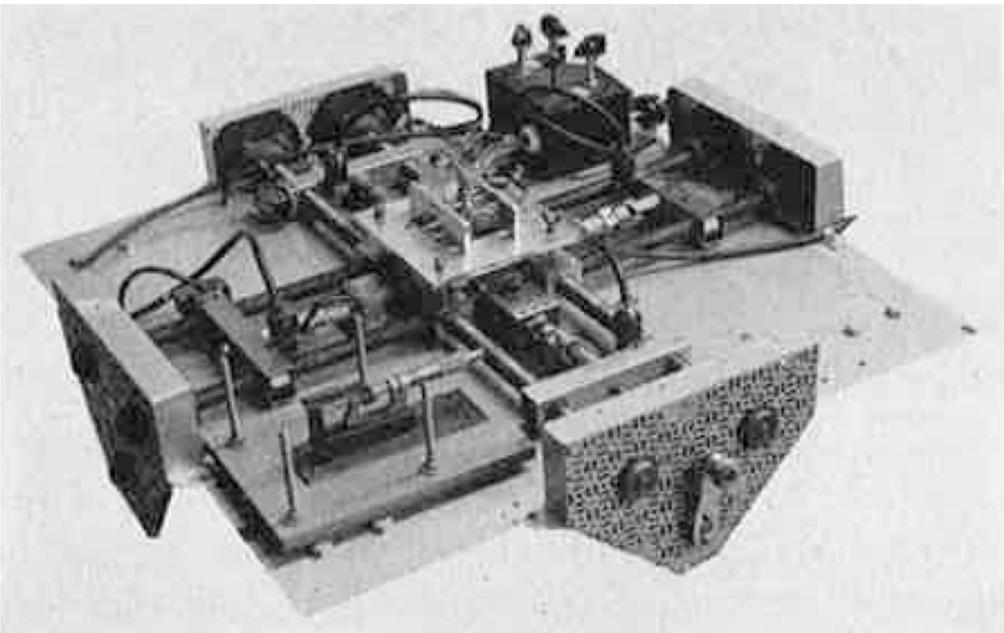

Figure 10: Klein biaxial tester, image adapted from (48)

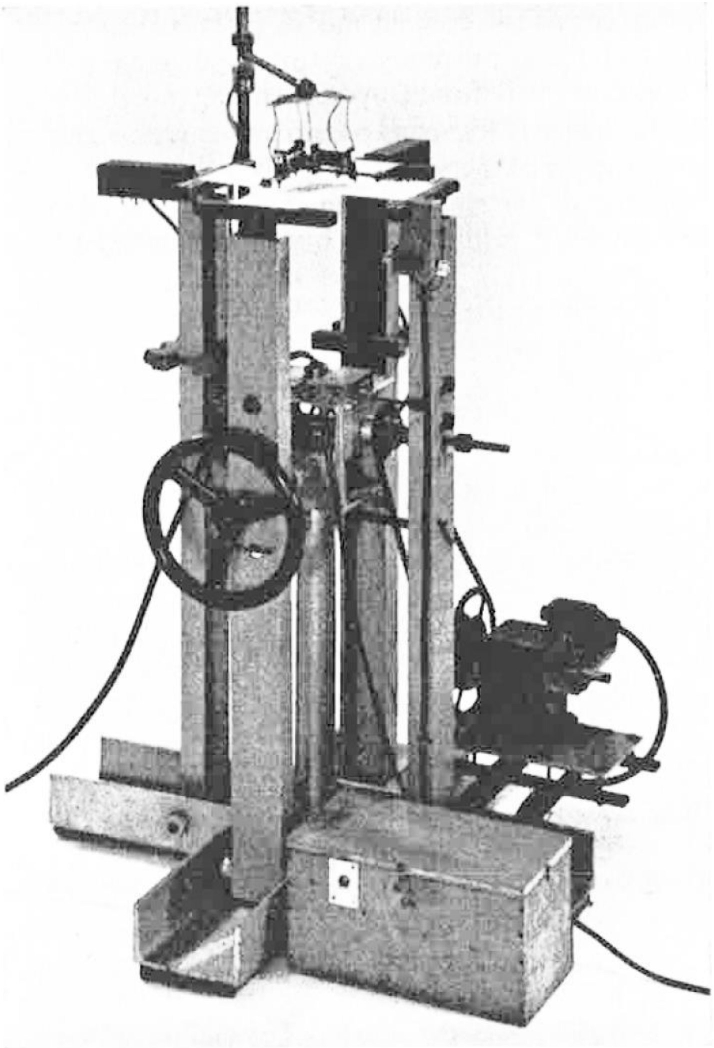

Figure 11: Clulow and Taylor tester, image adapted from (49)

Biaxial testers have a similar concept, two perpendicular loads to be applied on a specimen; however, the difference between these designs is the measurement accuracy, which is depended upon the sample shape and the clamping method used to hold the specimen. Clamping the specimen on a biaxial tester is a major problem because gripping the specimen allows the fabric near the clamps to undergo tensile strain in the direction of the clamps (24, 38).

The clamping method used to hold the sample in Checkland and Klein's biaxial testers was with straight, not segmented, solid clamps, which did not allow stress in the direction of the clamps near the gripped area (24, 38, 46, 50). In these biaxial testers, a homogenous distribution can't be achieved. Bassett et al (24, 38, 50) discussed different gripping arrangement shown Figure 12. In the cruciform test (A), only the central part of the sample undergo as biaxial tensile while the arms undergo a uni-axial tensile loads thus there is no need to have tensile in the other direction near the clamps and hence a solid clamp can be used. To avoid inhomogeneity in this method, the cross yarns in the specimen arms are removed to allow the central section to carry the load; however, this might produce inhomogeneity caused by the difference along the specimen arms yarns stiffness and crimp that is usually eliminated when the crossing yarns share the load. Similarly, the grab test (B) applies biaxial forces in the center of the sample, but the sample here is square and the cruciform shape is achieved inside the square. Both A and B methods don't produce a homogeneous stress distribution in the sample (24).

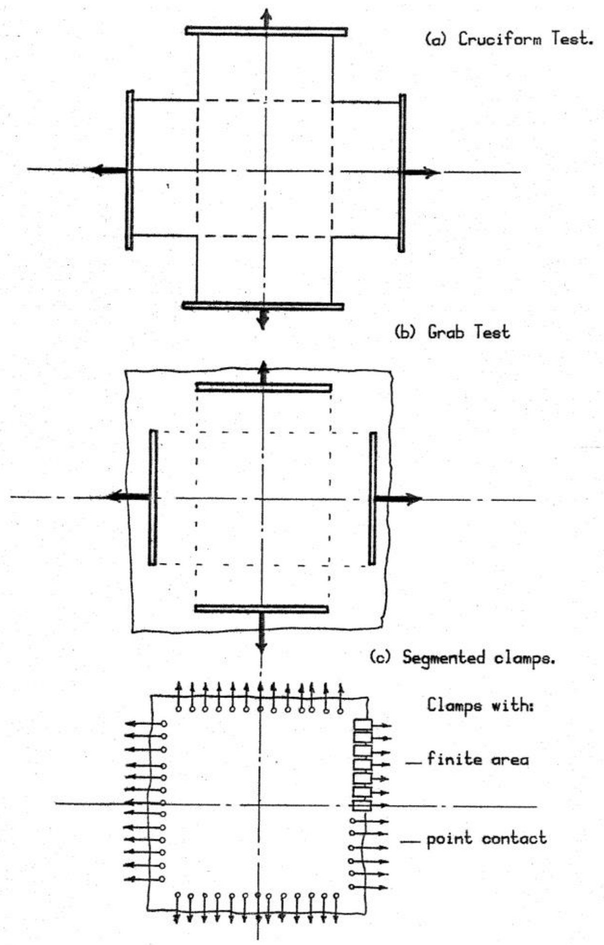

Figure 12: Biaxial tensile sample options, image adapted from (24)

This problem was solved by using segmented clamps of finite areas (24, 46) to allow movement along and near the direction of the clamps. Treloar (51) in 1948 was the first to use pins or segmented clamps on a square sample of rubber to apply homogenous strain. Kawabata et al (52) followed a similar concept in his work and used a square sample to measure the stress/strain in two directions, but he measured the stress over the center sections of the specimen sides. Later, MacRory et al (53) adopted the same method and gripped each side of the sample with 4 wire hooks per cm. The wires are connected to a coil spring through which a bar is inserted, this arrangement measures the fabric load applied on a single direction as a total of the spring forces on that direction.

Although this clamping method proved to have more homogenous stress over the sample, there might also be prone to have less stress near or between the clamps than in other parts of the sample (24).

It is appreciated that to measure accurately stress and strain in more than one direction, the design of the apparatus, the size and shape of the specimen and its clamping are complex and accuracy and efficiency are in question.

Many tried to simplify the design of biaxial testers and reduce their cost by achieving the biaxial straining or movement by a tensile tester attachment or a single engine machine. Reichardt et al (54) had produced a two-dimensional force extension tester for woven fabric, which can measure the forces developed in one direction as a function of strain in that direction when the fabric is being extended in two perpendicular directions. This works as an apparatus attachment to an Instron tensile tester. Clay (55) developed a similar attachment. Yasuhiro (56) on the other hand based his biaxial tester on a single motion source to provide strain on both direction at the same time. Recently, Boisse (57) developed a biaxial tester based on the same principal, Figure 13, with solid clamps to measure cruciform samples from which they removed the cross yarns in the sample's arms.

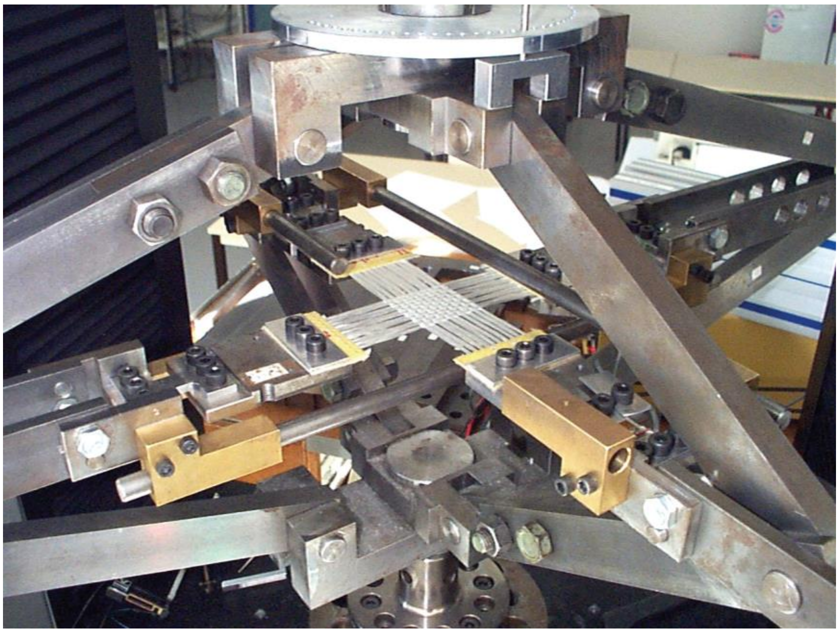

Figure 13: A biaxial device used by Boisse, image adapted from (57)

Although the biaxial tester attachments that are made to be installed on common extensometers can be very convenient and less expensive, the forces in the two directions can't be varied independently since they use one force applied and transferred into the sample on both directions. This makes the use of these attachments limited, as independent biaxial forces are important in order to fully assess the behaviour of the fabric by simulating real end use applications.

In real end uses, deformations such as tensile, bending, shear and compression rarely happen separately, but they almost always apply in combination during fabric processing and usage (4). Combined tensile and shear represent most applications, other out of plane deformations occur as well and they cause stresses in fabrics that are considered to act in-plane of the fabric, therefore it is not necessary to consider them (58). Many researcher investigated the combined deformation starting with Bassett (24, 38), who referred to testing the fabric as a tube, Figure 3, as a combined test between biaxial tensile and shear when the compression is applied with torque on the edge of the fabric. However, this method has limitation since the seam in this test has to be flexible and with negligible differences to the rest of the fabric and is mainly designed for industrial applications such as pneumatic structures (24).

Yendell (59) was the first to build a combined apparatus but Ghosh (46) referred to Freeston et al (58) as the first to use a biaxial tester with clamps that rotate around a perpendicular axis to apply shear deformation.

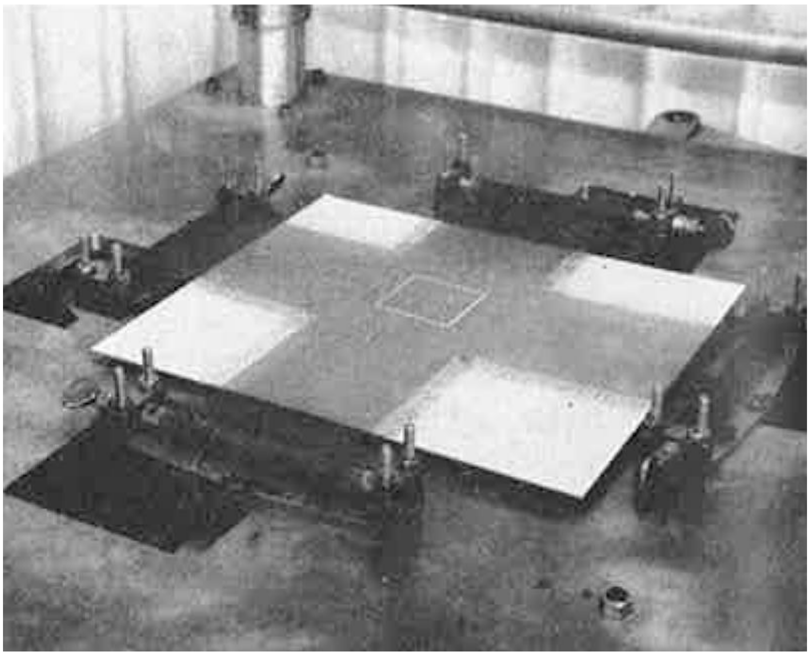

Figure 14: The combined tester used by Freeston, image adapted from (58)

Freeston's equipment, Figure 14, uses a cruciform sample clamped by jaws free to rotate about an axis perpendicular to the plane of the test, from which the tester can apply shear deformation on the sample. Load is applied by a hydraulic pump and strain is being measured photographically. The sample edges width are 4 inchs, the uniform biaxial stress is only 2X2 inch in the center of the sample. Although Freeston et al (58) mentioned that shear can be applied on the sample by rotating the clamps, they did not use the tester for combined tests and there is no shear results presented, moreover; Freeston and Sebring et al (60, 61) when they described the same tester, they did not mention this device's capability of applying shear, thus its capability to apply and measure combined stresses is in question.

Yendell (59) developed an apparatus that can apply simultaneous shear and biaxial tensile on a cruciform sample, Figure 15. Scardino and Ko (62) have used this instrument to investigate the behaviour of triaxial woven fabrics under shear and biaxial behaviour to prove that they are superior to normal woven fabrics for combined deformation applications.

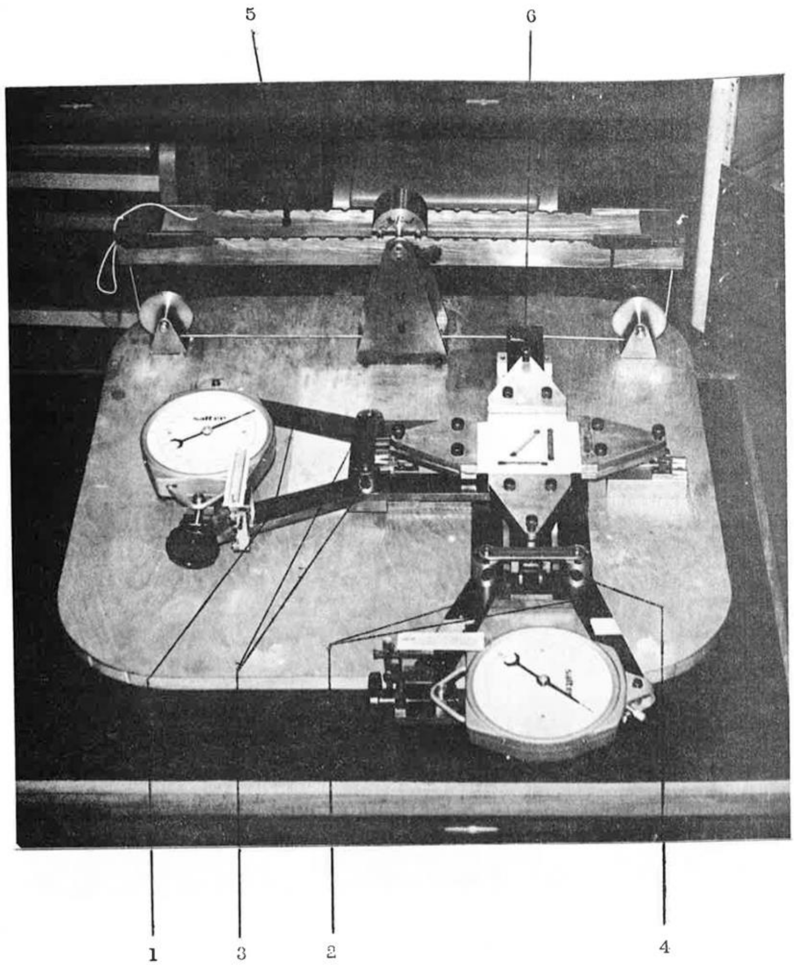

Figure 15: Yendell tester, image adapted from (59)

Loads in warp or weft direction are applied by spring balances that transfer the stresses to the fabric by means of bars (1 and 2). The bars are pivoted with the clamps at (3 and 4). Shear is achieved when the weft is being rotated in relation to the warp by moving the load in the see-saw beam (5), connected to the weft system by arm (6). The stress distribution in the sample is unbalanced due to the cruciform specimen and the pivots that allow the claps to rotate cause buckling at large deformation.

Later, Bassett (24) developed a testing machine able to test a biaxial tensile and apply shear at one of the axis, Figure 16. E, W, S, and N are moving crossheads and shear occurs in axis NS.

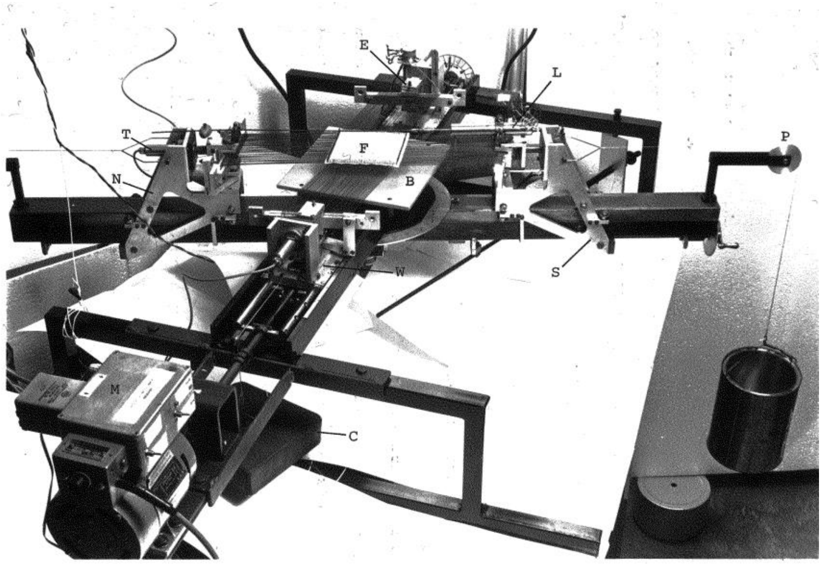

Figure 16: Bassett combined biaxial tensile and shear tester, image adapted from (24)

Bassett solved the problem of the inhomogeneity of the cruciform specimen by using a square sample and he used hooks in order to avoid the inhomogeneity developed by using solid clamps. However, this apparatus still rotates one set of yarns to achieve the shear before applying the biaxial deformation, increasing the risk of buckling the sample.

Stylios (1) developed an apparatus, the Fabric Automatic Measurement and Optimization Universal System (FAMOUS), Figure 17, that was able to automatically measure combined tensile and shear, by being able to move the fabric in two axis and at different loads and speed rates.

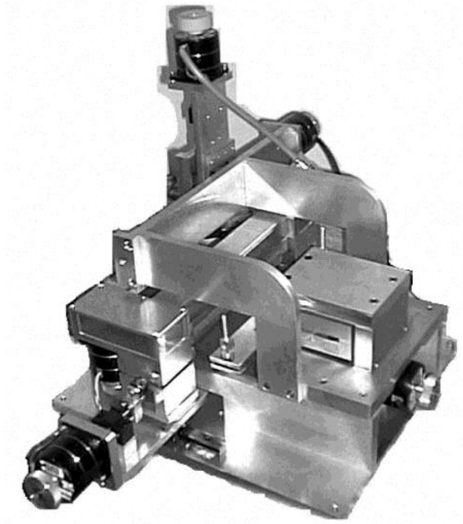

Figure 17: FAMOUS system, image adapted from (1)

Lately, Cavallaro and Sadegh et al (63-65) developed an equipment that applies biaxial stress and shear stress simultaneously, Figure 18.

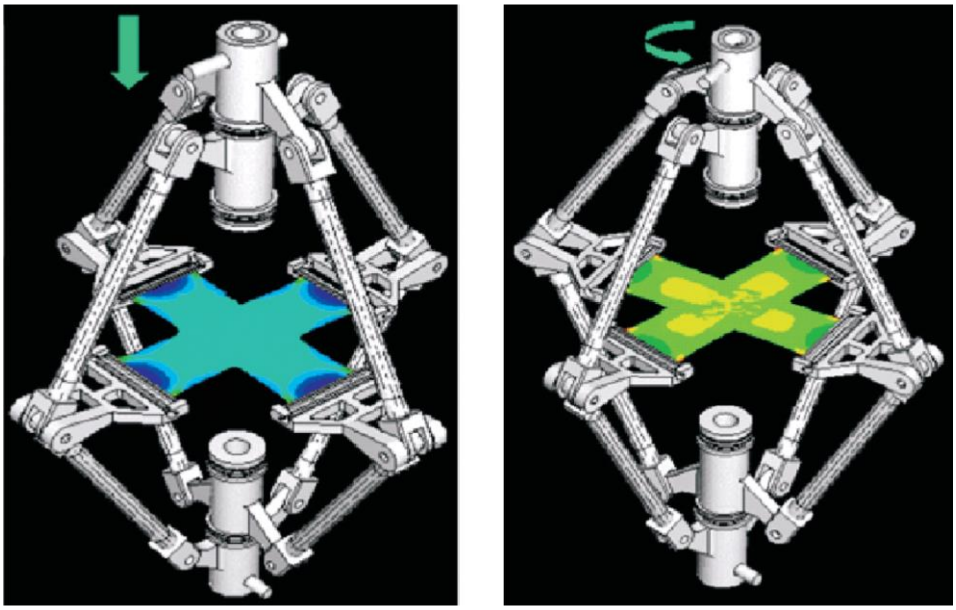

Figure 18: The combined biaxial tension and shear tester. The biaxial test (left). The shear test (right), image adapted from (63)

The up and down movement of the top part will result in pushing the clamps holders outward thus applying a biaxial stress, Figure 18 left. The shear is applied on the sample by moving the two sets in respect to the other, Figure 18 right. This tester uses a cruciform samples and it hasn't been used for convention fabrics.

Sadegh and Cavallaro et al (66) have developed another tester using a two scissor jack assemblies, an upper and a bottom one. The bottom assembly is attached to a turntable to allow rotation in respect with the upper assembly. A cruciform sample is attached to load clamps that are connected by the assembly hinges. Two load screws with motors open and close the assemblies in order to apply tensile and in-plane compression on the sample, the turntable will rotate by means of another motor and turn the bottom assembly to apply shear stress, Figure 19.

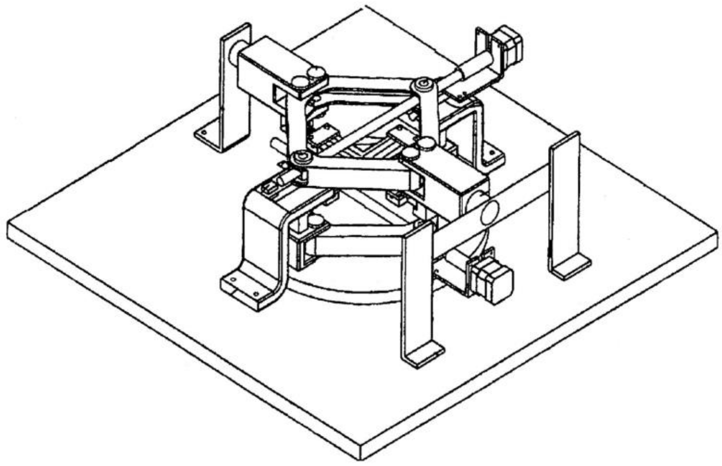

Figure 19: A combined tester by Sadegh, image adapted from (66)

In both previous testers, the fabric shear is applied by moving one set of clamps opposite to each other and rotating it in respect with the other set, which is a one-direction shear with the potential of buckling the sample at high shear degrees. These testers also measure cruciform specimens with solid clamps meaning that the inhomogeneity problems associated with these samples still exist. These testers have complicated mechanisms and many moving parts, which might lead to friction and complications and increase in operation process, maintenance and cost. The materials that these testers are designed to measure are glass fabrics with require high loads and low sensitivity, making their application for the standard fabric applications doubtful.

3 - Discussion and Conclusion

Measuring fabric's mechanical behaviour started during the Zeppelin era, before the need of measuring fabric handle. During that era there was a great need to measure the behaviour of the airship's envelop under different loads and thus tensile, shear and biaxial tension were measured. Later, the need to measure fabric handle for garments developed measurement methods for mechanical properties.

Although these measurements are useful in distinguishing fabrics, they do little in determining the behaviour of fabrics, as fabrics are imposed to multi axial loads combinations, rather than single axis stresses and strains. To this day researchers have been investigating multi-axial testers. Lynch et al (67) developed a three axis loading device to help applying load on three axises. Cavallaro et al (68) developed a mutli-plane triaxial tester to carry out shear and biaxial in the textile plane and compression on the vertical plane. Monteiro et al (69) developed an multiaxial tester that measure tensile at four axises, with 45° difference between them.

Du and Yu (26) classified fabric testing systems into two groups; SPST, as Single Property through Single Test and MPST, as Multiple Property through Single Test. They considered the SPST systems to be time consuming, expensive, but low in error (26), examples of the SPST systems are the KES and FAST instruments. MPST systems saved time and were less expensive, such as FAMOUS and CHES-FY. However both systems measured mechanical properties separately, except in the case of FAMOUS, which can measure combined loads.

The measurement of combined behaviour, and studying the interaction between them, has been studied by many researchers. Recently, more equipment that combine biaxial testing and different types of deformations have been developed. Although these equipment measure similar concepts, they differ in methods of measurement that produce different stress distribution in the sample and hence different results. The type of sample clamping, the shape and the size of the sample and the application method are the main factors that need to be considered when designing new tester that would effectively provide combined properties. These testers are not commercially available, have a very complicated structure for avoiding frictional interference, and have a difficult method of fabric measurement and interpretation of the data. It is therefore paramount to find a simple design that is free from any clamping and frictional movement of parts.

In conclusion, a universal apparatus that can measure combined properties at low and high loads is needed and the research community should focus its efforts on this area. This way, the behaviour of fabrics will be realistically measured and their development for fulfilling various end uses will be effective. This new apparatus should have a simple design without complicated assemblies, resulting in reliable and low cost universal equipment. A clamping method ensuring stability and equal strain distribution is necessary, bi-tensile and bi-shear should be applied on both principal axis at the same time to generate a homogeneous stress in the sample. This design of the apparatus should allow the measurement of standard fabrics at low loads as well as high performance fabrics of high loads.

Reference

1. Stylios GK. New Measurement Technologies for Textiles and Clothing. International Journal of Clothing Science and Technology. 2005;17(3/4):135 - 49.

2. M. Issam yousef, Stylios GK. Legacy of the Zeppelins: defining fabrics as engineering materials. The Journal of The Textile Institute. 2014;106(5):480 - 9.

3. Haas R. The Stretching of The Fabric and The Deformation of the Envelope in Nonrigid Balloons. Part I: The Stretching of the Fabric and The Shape of The Envelope. NACA, 1912 reported in English by Karl K. Darrowin 1917 Contract No.: Report No. 16.

4. R. C. Dhingra, S. D. E. Jong, Postle R. The Low - Stress Mechanical Properties of Wool and Wool Blend Woven Fabrics. . Textile of Research Journal. 1981;51(12):759 - 68.

5. Sueo Kawabata, Niwa M. Objective Measurement of Fabric Hand. In: Raheel M, editor. Modern Textile Characterization Methods. New York: Marcel Dekker; 1996. p. 329 - 54.

6. Kawabata S. The Standardization and Analysis of Hand Evaluation. Second Edition ed. Japan: The Hand Evaluation and Standardization Committee; 1980.

7. Boos AD. Concepts and understanding of fabric hand. In: Behery HM, editor. Effect of mechanical and physical properties on fabric hand. Cambridge: Woodhead Publishing Limited and CRC Press; 2005.

8. Harlock SC. Fabric objective measurement: 2, Principles of measurement. Textile Asia. 1989;20(7):66 - 71.

9. Pan N, Zeronian H, Ryu H-S. An Alternative Approach to the Objective Measurement of Fabrics Textile Research Journal. 1993;63(1):33 - 43.

10. Jin-Lian Hu, Zhang Y-T. The KES Shear Test for Fabrics. Textile Research Journal 1997;67(6):654 - 64.

11. Boos AGD, Tester DH. SiroFAST, Fabric Assurance by Simple Testing, A system of Fabric Objective Measurement and its Application in Fabric and Garment Manufacture. CSIRO Australia, 1997 Contract No.: WT97.02.

12. Kristina Ancutiene, Eugenija Strazdiene, Nesterova A. The Relationship between Fabrics Bending Rigidity Parameters Defined by KES-F and FAST Equipment. MATERIALS SCIENCE (MEDZIAGOTYRA). 2010;16(4):346 - 52.

13. Bishop DP. Fabrics: Sensory and Mechanical Properties. Textile Progress. 1996;26(3):1 - 57.

14. Hu J. Objective measurement technology of woven fabrics. Structure and mechanics of woven fabrics. Cambridge: Woodhead Publishing Limited; 2004. p. 21 - 60.

15. A. Hadj Taieb, S. Msahli, Sakli F. A New Approach for Optimizing Mechanical Clothing Tactile Comfort. Journal of Advanced Research in Mechanical Engineering. 2010;1(1):43 - 51.

16. Kadole PV. Fabric Assurance by Simple Testing. Colourage. 1995;42(9):27 - 30.

17. David Tester, Boos AD. Get it right FAST time. Textile Horizons. 1990;10(8):13.

18. S. M. Spivak, Treloar LRG. The Behavior of Fabrics in Shear. Part III: The Relation Between Bias Extension and Simple Shear. Textile Research Journal 1968;38(9):963 - 71.

19. Buckenham P. Bias-extension Measurements on Woven Fabrics. Journal of Textile Institute. 1997;88(1):33 - 40

20. Jurgite Domskiene, Strazdiene E. Investigation of fabric shear behaviour FIBERS & TEXTILES in Eastern Europe. 2005;13(2(50)):26 - 30.

21. Bona M. Physical properties of textile materials. Textile Quality Physical methods of product and process control. Italy: Texilia; 1994. p. 83 - 152.

22. Ozge Tokmak, Omer Berk Berkalp, Gersak J. Investigation of the Mechanics and Performance of Woven Fabrics Using Objective Evaluation Techniques. Part I: The Relationship Between FAST, KES-F and Cusick's Drape-Meter Parameters. FIBERS & TEXTILES in Eastern Europe. 2010;18(2(79)):55 - 9.

23. M. Y. Leung, T. Y. Lo, R. C. Dhingra, Yeung KW. Relationships between Fabric Formability, Bias Extension and Shear Behaviour of Outerwear Materials RJTA. 2000;4(2):10 -23.

24. Bassett RJ. The Biaxial Tensile and Shear Properties of Textile Fabrics and Their Application to the Study of Fabric Tailorability New South Wales: The Uneversity of New South Wales; 1981.

25. Hearle JWS. Shear and Drape of Fabrics. In: J. W. S. Hearle, P. Grosberg, Backer S, editors. Structural Mechanics of Fibers, Yarns, and Fabrics. 1. New York: Wiley-Interscience; 1969. p. 371 - 410.

26. Zhaoqun Du, Yu W. Study on strength property of fabric under low-stress condition. Journal of the Textile Institute 2008;99(3):265 - 72.

27. Du Zhaoqun, Zhou Tianxian, Zhen Gang, Weidong Y. In-Situ complex testing of fabrics stiffness and properties by a sensor. Applied Mechanics and Materials. 2011;48 - 49:617 - 20.

28. Zhaoqun Du, Weidong Y. A comprehensive handle evaluation system for fabrics: I. Measurement and characterization of mass and bending properties. Meas Sci Technol. 2007;18:3547 - 54.

29. Du Zhaoqun, Shen Hua, Zhou Tianxian, Zhen Gang, Zhou Xuchun, Weidong Y. Comparision of properties characterization between CHES-F, KES-F and FAST. industria textila. 2011;62(3):123 - 8.

30. V. Subramaniam, Sivakumar M. An Apparatus for Studying the Shear Behavior of Fabrics. Textile of Research Journal. 1988;58(7):430 - 2.

31. Jiaming Zheng, Takuga Komatsu, Yoshihiko Yazaki, Masayuki Takateva, and SI, Shimizu Y. Evaluating Shear Rigidity of Woven Fabrics. Textile of Research Journal. 2006;76(2):145 - 51.

32. V. Subramaniam, M. Sivakumar, V. Srinivasan, Sasikala M. Determining Factors that Affect Fabric Shear Behavior with the Twist Method. Textile of Research Journal. 1990;60(6):368 - 70.

33. Holt NL, inventor; Anamet Laboratories Inc, assignee. METHOD AND MEANS FOR BIAXIALLY TESTING MATERIALS. USA1980.

34. Brian M. Macrory, McNamara AB. Knitted Fabrics Subjected to Biaxial Stress - An experimental Study. Textie Research Journal. 1967;37(10):908 - 11.

35. Behre B. Mechanical Properties of Textile Fabrics. Part I: Shearing. Textile of Research Journal. 1961;31(2):87 - 93.

36. Stylios GK. Seam Pucker and Structural Jamming in Woven Textiles. Leeds: University of Leeds; 1983.

37. Culpin MF. THE SHEARING OF FABRICS: A NOVAL APPROACH. Journal of Textile Institute. 1979;70(3):81 - 8.

38. Bassett R, Postle R, Pan N. Experimental Method for Measuring Fabric Mechanical Properties: A Review and Analysis Textile Research Journal. 1999;69(11):866 - 75.

39. S. H. Chang, S. B. Sharma, Sutcliffe MPF. Microscopic investigation of tow geometry of a dry satin weave fabric during deformation. Composites Science and Technology. 2003;63:99 - 111.

40. P. Harrison, Potluri P. SHEAR TENSION COUPLING IN BIAXIAL BIAS EXTENSION TESTS. AIP conference proceedings; 9; Edinburgh - Scotland2009.

41. F. Abdiwi, P. Harrison, Z. Guo, P. Potluri, Yu WR. Measuring the Shear - Tension Coupling of Engineering Fabrics. The 14th International ESAFORM Conference on Material Forming: AIP Conference Proceedings; 2011.

42. Prasad Potluri, David A Ciurezu, Young RJ. Biaxial Shear Testing of Textile Preforms for Formability Analysis. 16th International Conference on Composite Materials; Kyoto Japan2007. p. 1 - 4.

43. P. Harrison, F. Abdiwi, Z. Guo, P. Potluri, Yu WR. Characterising the shear-tension coupling and wrinkling behaviour of woven engineering fabrics. Composite: Part A. 2012;43:903 - 14.

44. John Thronton, Liddell I. Tensile structure. In: Alan Blanc, Michael McEvoy, Plank R, editors. Architecture and Construction in Steel. London: E & FN SPON; 1992. p. 289 - 318.

45. Wittendorfer F. die halle Luftschiffe zwischen Biesdorf und Karlshorst. Berlin: Kulturring in Berlin e.V; 2007.

46. Ghosh TK, inventor; North Carolina State University, assignee. APPARATUS AND METHOD FOR BIAXIAL TENSILE TESTING OF MEMBRANE MATERIALS. USA2002.

47. P. B. Checkland, T. H. Bull, Bakker EJ. A Two-Dimensional Load-Extension Tester for Fabrics and Film. Textie Research Journal. 1958;28(5):399 - 403.

48. Klein WG. Stress-Strain Response of Fabrics under Two-Dimensional Loading, Part I: The FRL Biaxial Tester. Textie Research Journal. 1959;29(10):816 - 21.

49. Elaine E. Clulow, Taylor HM. An Experimental and Theoretical Incestigation of Biaxial Stress Strain Relations in A Plain Weave Cloth. Journal of Textile Institute Transactions. 1963;54(8):T323 - T51.

50. Richard J Bassett, Postle R. Grip Point Spacing Along the Edges of an Anisotropic Fabric Sheet in a Biaxial Tensile Test. POLYMER COMPOSITES. 1999;20(2):305 - 13.

51. Treloar LRG. Stresses and Birefringence in Rubber subjected to General Homogeneous Strain. Proceedings of the Physical Society. 1948;60(2):135 - 44.

52. S. Kawabata, Masako Niwa, Kawai H. The Finit-Deformation Theory of Plain-Weave Fabrics. Part I: The Biaxial-Deformation Theory. The Journal of The Textile Institute. 1973;64(2):21 - 46.

53. Brian M. MacRory, J. Roger Mccraith, MCNamara AB. Experimental Investigation of the Biaxial Load-Extension Properties of Plain, Weft-Knitted Fabrics. Textie Research Journal. 1977;47(4):233 - 9.

54. C.H. Reichardt, H.K. Woo, Montgomery DJ. A Two-Dimensional Load-Extension Tester for Woven Fabrics. Textie Research Journal. 1953;23(6):424 - 8.

55. Clay SB, inventor; The United States of America as represented by the Secretary of the Air Force, assignee. BIAXIAL TENSILE APPARATUS. USA1999.

56. Hanabusa Y, inventor; Mitsubishi Materials Corporation, assignee. BIAXIAL TENSILE TENSILE MACHINE. Japan2011.

57. Pihilippe Boisse, Bassem Zouari, Gasser A. A mesoscopic approach for the simulation of woven fibre composite forming. Composites Science and Technology. 2005;65:429 - 36.

58. W.Denney Freeston, Milton M. Platt, Schoppee MM. Mechanics of Elastic Performance of Textile Materials. Part XVIII: Stress-Strain Response of Fabrics under Two Dimensional Loading Textie Research Journal. 1967;37(11):948 - 75.

59. Yendell MJ. A Sailcloth Testing Machine for Routine Use. Southampton: University of Southampton, 1971 SUYR Report No 32 Contract No.: 32.

60. R. E. Sebring, Freeston WD. Biaxial Tensile Tester for Fabrics. Dedham Massachusetts: Fabric Research Laboratories, General Equipment and Packing Laboratory and US Army Natick Laboratory, 1967 67-71-GP.

61. R. E. Sebring, M. M. Schoppee, W. D. Freeston, Monego CJ. Biaxial Tensile Tests of Coated Fabrics. Dedham, Massachusetts: Fabric Research Laboratories and US Army Natick Laboratories, 1969 69-75-GP.

62. Frank L. Scardino, ko FK. Triaxial Woven Fabrics. Part I: Behavior Under Tensile, Shear and Burst Deformation. Textile Research Journal. 1981;51(2):80 - 9.

63. Paul V. Cavallaro, and AMS, Quigley CJ. Decrimping Behaviour of Uncoated Plain - woven Fabrics Subjected to Combined Biaxial Tension and Shear Stresses. Textile Research Journal. 2007;77(6):403 - 16.

64. Paul V. Cavallaro, Claudia J. Quigley, Sadegh AM, inventors; The United States of America as represented by the Secretary of the Navy, assignee. COMBINED IN-PLANE SHEAR AND MULTI-AXIAL TENSION OR COMPRESSION TESTING APPARATUS. USA2005.

65. Ali M. Sadegh, Paul V. Cavallaro, Quigley CJ, inventors; The United States of America as represented by the Secretary of the Navy, assignee. BIAXIAL AND SHEAR TESTING APPARATUS WITH FORCE CONTROLS. USA patent US 7204160B1. 2007.

66. Ali M. Sadegh, Paul V. Cavallaro, Quigley CJ, inventors; The United States of America as represented by the Secretary of the Navy, assignee. COMPACT AND STAND-ALONE COMBINED MULTI-AXIAL AND SHEAR TEST APPARATUS. USA2011.

67. Edward J. Lynch, Gray DT, inventors; The United States of america as represented by the Administrator of the National Aeronautics and Space Administration, assignee. THREE-AXIS, ADJUSTABLE LOADING STRUCTURE. USA1973.

68. Paul V. Cavallaro, Sadegh AM, inventors; The United States of America as represented by the Secretary of the Navy, assignee. TRIAXIAL TENSION COMPRESSION SHEAR TESTING APPARATUS. USA2006.

69. Joao Monteiro, Ana DaRocha, Mario Lima, Julio Martins, Mario deAraujo, Carlos Couto, et al., inventors; Universidade do Minho, assignee. MULTIAXIAL UNIVERSAL TESTING MACHINE. USA2009.